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Vector tactile sensing by a single sensor element of vibratory microcantilever based on multimode resonant frequency shift

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Abstract

Vibratory force sensors have been fabricated using piezoelectric capacitors on microcantilevers for triaxial sensitivity by a single sensor element. The cantilevers have been formed into three-dimensionally curved shape by controlling residual stress combination of the multilayered structure. Triaxial tactile sensitivity of the cantilever has been analyzed under a load application onto the surface of an elastomer in which the cantilever is embedded. The cantilever is converse-piezoelectrically excited by an external ac voltage and three resonant modes have been developed to detect the applied load vector components by individual sensor element. The applied load vectors are estimated by measured resonant frequencies of the single cantilever sensor in an error less than 1.1% to the full scale of the load 4 kPa.

Keywords Tactile sensing, vector measurement, piezoelectric sensor, resonant frequency ;

1. Introduction

Miniaturized tactile sensors have been increasingly investigated for precise touch sensing on robots especially for nursing-care applications against the recent rapid increase of the aged population. Mincromachined multiaxial tactile sensors have been developed using strain-gauge cantilevers embedded in an elastomer material mimicking human skin. They have sensitivities to stress along with one normal and two shear directions caused by applied load on the elastomer surface, by using horizontal and vertical cantilevers [1] or using a combination of slanted cantilevers [2]. However, multiaxial sensitivity by a single sensor element is required for high-density integration into a sensor array. Moreover, vector measurement by the sensor elements placed at different locations might cause a measure error.

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In this work, the authors propose a vibratory piezoelectric cantilever sensor for vector tactile sensing. Fabricated sensor device formed in a proper curved shape by residual stress control is introduced, and triaxial sensitivity by the individual sensor element is demonstrated.

2. Sensor Structure

Figure 1 shows a schematic illustration of the cross-section of the layered structure of the cantilever and photographs of a fabricated cantilever sensor. A piezoelectric lead-zirconate-titanate (PZT) capacitor sandwiched between the bottom electrode of platinum and titanium films and the top electrode of gold film was formed on the SiO_2 layer. The PZT film was prepared by a conventional sol-gel method, Pt, Ti and Au films were deposited by using rf magnetron sputtering and SiO_2 layer was formed by thermally oxidization of the silicon substrate. Since the sol-gel derived PZT has tensile residual stress and thermally oxidized SiO_2 has compressive one, the cantilever structure spontaneously stands up from the substrate when the underneath silicon is removed. The silicon substrate was etched by using reactive ion deep etching technique from the backside.

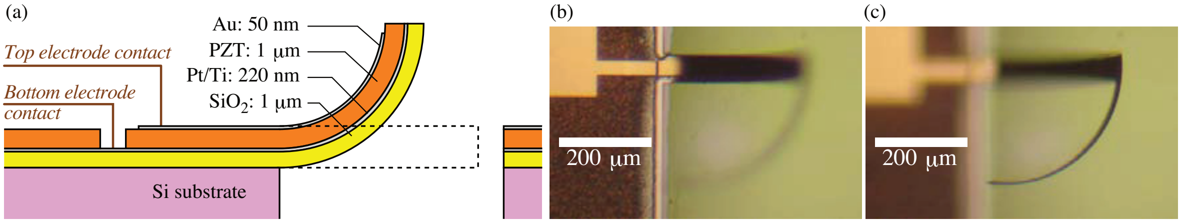

Fig.1. (a) a schematic illustration of the cross-section of the layered structure of the cantilever sensor, and top-view photographs of the fabricated cantilever sensor (b) focused on the substrate and (c) focused at the tip of the cantilever.

The cantilever was formed in an L-shape sized as 50 μm wide and 400+400 μm long on the substrate surface. After released from the substrate, the cantilever curled up from the substrate as shown in the photographs focused on the substrate in Fig. 1 (b) and focused at the tip of the cantilever in Fig. 1 (c). The cantilever firstly curves upward from the substrate and then curves to the right. The final geometry of the cantilever has been designed according to the stress-rigidity information. The curvatures of the two parts of the cantilever were well controlled as 255 μm to adjust the curve angles to 90°. This three-dimensionally curved shape is needed for the triaxial tactile sensitivity.

3. Axial Sensitivity Analysis

Axial tactile sensitivity of the L-shape curved cantilever structure embedded in an elastomer material was investigated through finite element analysis (FEA). Figure 2 illustrates the analysis model of the cantilever-elastmer system. The PZT/SiO_2-bilayer cantilever is embedded in PDMS (polydimethyl siloxiane) elastomer. The cantilever is excited by an ac 5 V, and loads P_x, P_y and P_z are applied on the elastomer surface. Resonant frequency shifts of the vibrating cantilever upon the load application were analyzed using FEA software, ANSYS academic teaching introductory version 12.1. Figure 3 shows the cantilever shape and its vibration modes developed in the analysis. The tip part mainly vibrates at the first mode, the root part mainly vibrates at the second mode, and the both parts vibrate at the third mode. These three vibration modes were used for tactile sensing.

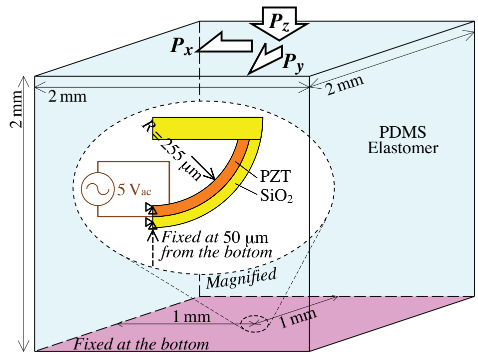

Fig. 2. Schematic illustration of analysis model for the piezoelectric vibratory cantilever in PDMS elastomer.

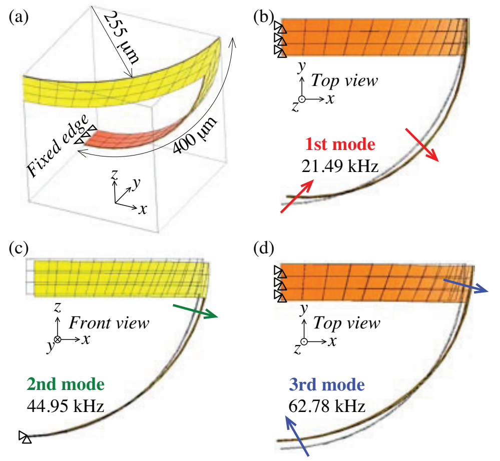

Fig. 3. (a) bird's eye view of the cantilever structure, and vibration modes at (b) the first, (c) the second and (d) the third resonant frequencies.

Figure 4 shows the resonant frequency shifts in the three modes versus the applied loads P_x, P_y and P_z. Here the relative resonant frequency shift F is defined as $F = (f' - f_0)/f_0$ where f_0 is the resonant frequency without a load and f' is the shifted resonant frequency upon a load application. The frequency shifts in the three modes show clearly linear dependence on all the loads along with the three axes. The linear coefficients are shown in Table 1. Figure 4 (d) shows that the frequency shift to the loads can be superposed, that is, $F(P_x, P_y, P_z) \approx F(P_x, 0, 0) + F(0, P_y, 0) + F(0, 0, P_z)$. The total nonlinearity is less than 6% in the range of load 4 kPa. Thus the forward problem (conversion from load vector $\boldsymbol{P}$ to frequency shift vector $\boldsymbol{F}$) is expressed as $\boldsymbol{F} = \boldsymbol{AP}$ where their components are

$$\begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix} = \begin{pmatrix} a_{1x} & a_{1y} & a_{1z} \\ a_{2x} & a_{2y} & a_{2z} \\ a_{3x} & a_{3y} & a_{3z} \end{pmatrix} \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}. \tag{1}$$

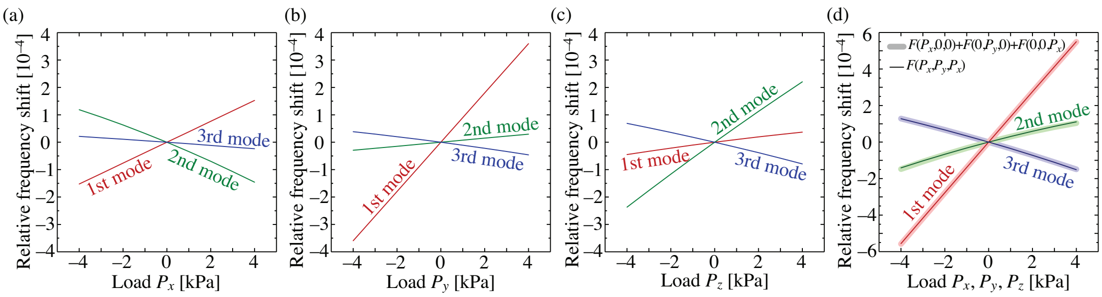

Fig. 4. Relative resonant frequency shifts of the three modes versus applied load; (a) on the single x-axis, $F(P_x, 0, 0)$, (b) on the single y-axis, $F(0, P_y, 0)$, (c) on the single z-axis, $F(0, 0, P_z)$, and (d) light-colored thick curves for the sum of the shifts on the three axes, $F(P_x, 0, 0) + F(0, P_y, 0) + F(0, 0, P_z)$, and sharp-colored thin curves for the shifts on the triaxial load, $F(P_x, P_y, P_z)$.

Table 1. Coefficients of the relative resonant frequency shift to the applied load [10 ^{6}kPa ^{1}]. Each coefficient corresponds to a component of the system matrix $\boldsymbol{A}$ in Eq. (1), which is derived from the results shown in Fig. 4 (a)~(c).

$\dfrac{\partial \boldsymbol{F}}{\partial \boldsymbol{P}}$	$\dfrac{\partial \boldsymbol{F}}{\partial P_x}$	$\dfrac{\partial \boldsymbol{F}}{\partial P_y}$	$\dfrac{\partial \boldsymbol{F}}{\partial Pz}$
$\dfrac{\partial F_1}{\partial \boldsymbol{P}}$	$a_{1x} = 38.1$	$a_{1y} = 89.9$	$a_{1z} = 10.2$
$\dfrac{\partial F_2}{\partial \boldsymbol{P}}$	$a_{2x} = -33.1$	$a_{2y} = 7.4$	$a_{2z} = 57.2$
$\dfrac{\partial F_3}{\partial \boldsymbol{P}}$	$a_{3x} = -5.6$	$a_{3y} = -10.6$	$a_{3z} = -18.5$

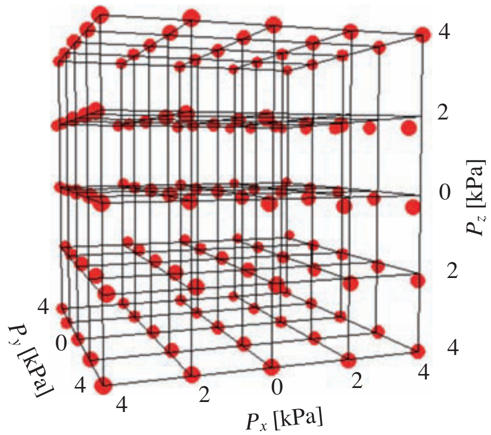

Fig. 5. The results of the tactile load estimation by the single cantilever sensor. Circles indicate the estimated load vectors by their positions in P_x-P_y-P_z space.

4. Applied Load Estimation

Tactile sensing is realized by solving the inverse problem $\boldsymbol{P} = \boldsymbol{A}^{-1}\boldsymbol{F}$ from the measured frequency shift vector $\boldsymbol{F}$. Figure 5 shows the load estimation result by the inverse system with compensating the nonlinearity using a transfinite mapping technique. The circles indicate the estimated load vectors by their position in P_x-P_y-P_z space, with exaggerated errors by ten times. The maximum estimation error is less than 43 Pa in the load range of 4 kPa, which corresponds to the load pressure holding an adult.

5. Conclusions

Piezoelectric cantilever sensors have been fabricated in a curved shape owing to residual stress combination of PZT and SiO_2 films. Vibration modes of the L-shaped curved cantilever embedded in PDMS elastomer has been analyzed in therms of frequency shift upon a load application on the elastomer surface. The results show that vector components of the applied load can be estimated by using a single sensor element.

Acknowledgements

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References

[1] Tanaka Y, Nakai A, Iwase E, Goto T, Matsumoto K, Shimoyama I. Triaxial tactile sensor chips with piezoresistive cantilevers mounted on curved surface. APCOT 2008; 1B1-1.

[2] Huang Y-M, Sohgawa M, Yamashita K. Kanashima T, Okuyama M, Noda M, Noma H. Fabrication and normal/shear stress responses of tactile sensors of polymer/Si cantilevers embedded in PDMS and urethane gel elastomer. *IEEJ Trans. SM* 2008;**128**:193-7.